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Simulation Models for MIMO Wireless Channels

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Abstract

In recent years, with the excellence performance in the system spectrum efficiency, MIMO technology has become the concerned topic in the mobile communication technology development process. In order to make better use of MIMO technology, the characteristics of MIMO channel had to be studied, and it is inevitable to accurately model and simulate MIMO wireless channels in different conditions. Wireless communication environment is very complex, so it is difficult to modeling of MIMO channel. In this paper, carrier wave frequency, the maximum Doppler frequency shift, AOA (Angle of Arrival) distribution, power azimuth spectrum and adjacent antenna spacing were taken into account integrating. Expressions of the spatial correlation coefficient for different power azimuth spectrum (PAS) distributions were studied. A MIMO channel model was brought forward which has spatial selectivity, frequency selectivity, and time correlation. Simulation shows this related channel capacity is consistent with theoretical channel capacity. Thereby the rationality of this modeling was validated. This model provides powerful implement for simulation of MIMO capability, analysis of system capacity and evaluation of performance.

Keywords: *MIMO, wireless channel, channel model, spatial correlation*

1. Introduction

The performance of mobile communication system mainly was restricted by the wireless channel. Generally there are complex terrains between the transmitter and receiver propagation path. The channel is often irregular and unpredictable, with complex time-varying properties of wave propagation, resulting in channel analysis and propagation prediction difficulty. With the development of communication system is becoming more complex, wireless channel modeling and simulation for digital mobile communication systems have become more and more important. The concrete is mainly manifested in the following three aspects:

The searching of optimal modulation and demodulation scheme, the optimal source channel coding scheme and the best channel equalization scheme suitable for different mobile channel environments must be based on the wireless channel modeling. The developing efficient wireless channel simulator, so as to effectively test the performance of components of mobile communication system must be based on the wireless channel modeling. Wireless channel modeling could provide the scientific basis for cellular coverage, base station layout and system designed, so as to reduce the blindness.

Today, the wireless spectrum resource is relative insufficient, multiple input multiple output (MIMO) system has shown its superiority. Information theory has proved that, when different receiving antenna and the transmitting antenna is entirely unrelated, MIMO system can better improve the performance of resistance to fading and noise, thereby obtaining the enormous capacity. For example: when the receiving antenna and the transmitting antenna number is 8, and the average SNR is 20dB, link capacity can be as high as 42bit/s/Hz. this is 40 times of capacity that the single antenna system can reach. Therefore, MIMO technique can achieve high data rate, improve the system capacity, and increase the transmission quality. The presupposition is that environment has rich scattering and channel matrix has low relativity or irrelevant (except Keyhole effect) [1-2]. But practical communication channel often has not perfect rich scattering. At the same time, fading channel maybe has relativity owing to antenna distributing, antenna spacing, DOA (Direction of Arrive) and angle spread. This relativity would depress channel capacity more or less. In order to improve the performance of MIMO, the characteristic of the wireless channel should be studied. The MIMO channel model could be

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used to evaluate relate performance of all kind of MIMO, also could be used to analyze the affection on channel capacity coming from the antenna parameters in order to make better system designed [3-7]. So, in recent years, there are many researches about channel model base on the channel characteristic [8-10].

In this paper, carrier wave frequency, the maximum Doppler frequency shift, AOA (Angle of Arrival) distribution, power azimuth spectrum and adjacent antenna spacing were token into account integrating. A MIMO channel model was brought forward which has spatial selectivity, frequency selectivity, and time correlation.

2. MIMO channel model

2.1 The characteristics of wireless channel

Study on the characteristics of wireless channel can lay theoretical foundation for wireless channel modeling.

The ways of electromagnetic wave propagation in free-space are direct, reflection, scattering, and diffuse. Wireless communication carries out information transmission based on the electromagnetic wave propagation in the space. The signal arriving at the receiving end has distortion compare with at the transmitting end after the spatial spread. The transmission attenuation of signal will be generated in the wireless channel. Transmission attenuation is related to the transmission path length and the disturbance in the transmission path.

In the wireless signal propagation process, many factors will lead to multipath fading, mainly including: signal transmission bandwidth, multipath propagation caused by reflector and the scattering body, the speed of a mobile station and the surrounding moving object. Multipath propagation will result in frequency selective fading and time delay spread.

When the relative movement of the signal transmitter and receiver occurs, the received signal spectrum has changed. This phenomenon is called the Doppler effect. Doppler extension leads to time selective fading.

The broadening of the emission angle causes by the multipath reflections and scattering. The widening of the arrival angle causes by the multipath signal arriving at the antenna array. Angle expansion can lead to spatially selective fading

Representative values of time delay spread, Doppler spread and angle spread were given in Table 1.

Table 1. Representative values of time delay spread, Doppler spread and angle spread [11]

Environment	time delay spread / μs	Doppler spread /Hz	angle spread /°
Indoor (micro unit)	0.1	5	360
The mall (micro unit)	0.3	10	120
City (macro)	5	120	20
Hilly (macro)	20	190	30
The flat countryside (macro)	0.5	190	1

2.2 MIMO channel model classification

There are different classifications of MIMO channel model in different documents. The MIMO channel model could be divided into four categories usually.

Broadband model and narrowband model:

The MIMO channel model could be divided into broadband model and narrowband model according to the system bandwidth. Most of the MIMO signal detection algorithms are based on narrowband model research. Broadband system can be converted to narrowband system by using the technology of OFDM. Usually, broadband MIMO channel model might be modeling according to power delay profile adding parameter influence based on the narrow band model.

Deterministic model and stochastic model:

Deterministic model is based on the accurate description of a particular communication environment of a model. There are two kinds of deterministic methods can be used to extract the characteristics of the channel: ray tracing and recording channel impulse response method. Stochastic model of the channel is viewed as a random process, and indirectly reflects the

MIMO channel statistical characteristics through a random process modeling. Stochastic model includes three kinds: geometric channel model, parametric channel model and the channel model based on the correlation.

Field measurement model and the scattering body model:

MIMO channel characteristics can be achieved to the measurement data for research and obtained, and then the channel could be modeling as having similar characteristics. In addition, a model is given based on scattering environment as far as possible to meet the characteristics of channel.

Non physical model and physical model:

A non physical model is based on the non physical parameters of the channel statistics. Usually, a non physical model is easy to simulation, and can provide accurate channel characteristics for simulating. But they reflected only the limited MIMO channel propagation characteristics, and rely on measuring equipment. Another class of models is based on the physical characteristics of the model of channel. Usually, some important parameters were selected to describe the MIMO propagation channel. Typical parameters include: angle of arrival, departure and arrival time perspective.

2.3 The typical MIMO channel model

IST METRA plan model:

This model is a kind of random non physical MIMO wireless channel model, and through field measurement activities to verify its correctness.

C. Xiao model:

This model is put forward by C. Xiao based on channel spatial correlation characteristics and statistic characteristics of the MIMO channel model. C. Xiao model add the effect of the transmission filter and the receiving filter

"one-ring" model:

In the "one-ring" model, the position of base station is assumed as higher. The base station was not surrounded by local scattering barrier, while the mobile stations are surrounded by scattering body. At the same time the propagation assumed between base station and mobile station is assumed as NLOS propagation. The model is applicable to the macro cell environment.

"two-ring" model:

In the "two-ring" model, there is not direct path between base station and mobile station. Only the close local scattering effect was considered. Due to the larger path loss and ignore the distal scattering effect was ignored. The model is applied to a microcell or indoor environment.

3. MIMO system model

In a MIMO system which has M_T transmitting antennas and M_R receiving antennas, the channel is FIR frequency selective and the order of this channel is L. The noise at the receiving end is white Gaussian noise and is irrelevance with transmitting signal. Under these hypotheses, the receiving signal could be denoted as

$$x_i(n) = \sum_{j=1}^{M_T} \sum_{l=0}^{L-1} h_{ij}(n,l) s_j(n-l) + v_i(n) \tag{1}$$

$1 \le i \le M_R$, $-\infty \le n \le +\infty$

In the system model as equation (1), $h_{ij}(n,l)$ denotes lth channel coefficient from jth transmitting antenna to ith receiving antenna at the time of n. $s_j(n)$ denotes the transmitting signal from jth transmitting antenna at the time of n. $v_i(n)$ denotes additive white Gauss noise on ith receiving antenna at the time of n. Let

$$\boldsymbol{H}(l)=\begin{bmatrix} h_{11}(n,l) & h_{12}(n,l) & \cdots & h_{1M_R}(n,l) \\ h_{21}(n,l) & h_{22}(n,l) & \cdots & h_{2M_R}(n,l) \\ \vdots & \vdots & \ddots & \vdots \\ h_{M_T1}(n,l) & h_{M_T2}(n,l) & \cdots & h_{M_TM_R}(n,l) \end{bmatrix} \quad (2)$$

4. Modeling of MIMO time-varying channel

4.1 Establish MIMO flat fading channel

First, L MIMO flat fading channel matrices $\boldsymbol{H}(l)$ are established by using modified Jakes simulation algorithm. $\boldsymbol{H}(l)$ has $M_T \times M_R$ dimensions.

$$h_{ij}(n,l)=h_{ij}^c(n,l)+\mathrm{j}h_{ij}^s(n,l) \quad (3)$$

$$1 \le i \le M_R,\ 1 \le j \le M_T,\ 0 \le l \le L-1$$

$$h_{ij}^c(n,l)=\sqrt{\frac{2}{N}}\left[\sum_{k=1}^{M} 2\cos\frac{\pi k}{M}\cos\left(2\pi f_d n\cos\frac{2\pi k}{N}+\phi_i\right)+\cos(2\pi f_c n+\phi_0)\right] \quad (4)$$

$$h_{ij}^s(n,l)=\sqrt{\frac{2}{N}}\left[\sum_{k=1}^{M} 2\sin\frac{\pi k}{M}\sin\left(2\pi f_d n\cos\frac{2\pi k}{N}+\phi_i\right)+\cos(2\pi f_c n+\phi_0)\right] \quad (5)$$

In the equation (3), (4) and (5), f_c is carrier wave frequency, f_d is the maximum Doppler frequency shift, N is the number of the harmonic, and $N=4M+2$, $\phi_i,(i=0,1,\cdots,M)$ are random variables in $[0,2\pi)$ which obey uniform distribution. Based on the central limit theorem, Gauss random process could be established by superimposed infinite weighted harmonic function which has offset frequency and random phase. This means $N \to \infty$.

4.2 Establish MIMO channel array correlation matrix

L MIMO flat fading channel matrices $\boldsymbol{H}(l)$ have been established by using modified Jakes simulation algorithm. But these matrices have not take account of spatial correlation. The calculation method of spatial correlation function would be introduced below.

Power azimuth spectrum is distribution of signal power spectrum density in the angle. It reflects the dispersion degree of power spectrum in space. Table 2 lists the canonical distribution of power azimuth spectrum in different communication environments [11].

Table 2. Distribution types of power azimuth spectrum in different communication environments

Environment	Base station	Mobile station
Macro cell	Laplasse distribution	uniform distribution
Minimal area	Truncated Gauss distribution	uniform distribution
A picocell	uniform distribution	uniform distribution
Indoor	uniform distribution	uniform distribution

Through actual measurement, AOA distribution might be cosine shape or bell shape. Uniform distribution, truncated Gauss distribution and truncated Laplasse distribution are in common use.

Power azimuth spectrum of uniform distribution is

$$p(\theta)=\frac{1}{2\Delta},\qquad \theta\in[\Theta-\Delta,\Theta+\Delta] \tag{6}$$

Power azimuth spectrum of truncated Gauss distribution is

$$p(\theta)=\frac{Q}{\sqrt{2}\pi\sigma}\exp\left[-\frac{(\theta-\Theta)^2}{2\sigma^2}\right],\qquad \theta\in[\Theta-\Delta,\Theta+\Delta] \tag{7}$$

Power azimuth spectrum of truncated Laplasse distribution is

$$p(\theta)=\frac{Q}{\sqrt{2}\sigma}\exp\left(-\frac{\sqrt{2}|\theta-\Theta|}{\sigma}\right),\qquad \theta\in[\Theta-\Delta,\Theta+\Delta] \tag{8}$$

In the equation (6), (7) and (8), Q is normalization constant and $Q=\left[1-\exp\left(-\frac{\sqrt{2}\Delta}{\sigma}\right)\right]^{-1}$. Θ is AOA of base station, Δ is angle spread.

Power azimuth spectrum is related to spatial correlation function. Correlation coefficients could be figure out by using equation (9) whichever distribution power azimuth spectrum obey.

$$\rho(d)=\int_{-\pi}^{\pi}p(\theta)\exp\left(\mathrm{j}\frac{2\pi d}{\lambda}\sin\theta\right)\mathrm{d}\theta \tag{9}$$

In the equation (9), d is space between adjacent antenna, λ is wavelength. The channel matrices at transmitting end (receiving end) could be denoted as equation (10).

$$\boldsymbol{R}_{Tx}=\begin{bmatrix}1 & \rho_{12} & \cdots & \rho_{1M_T}\\ \rho_{21} & 1 & \cdots & \rho_{1M_T}\\ \vdots & \vdots & 1 & \vdots\\ \rho_{M_T1} & \rho_{M_T2} & \cdots & 1\end{bmatrix} \tag{10}$$

ρ_{ij} is correlation coefficient from ith antenna to jth antenna at transmitting end, and $\rho_{ij}=\rho_{ji}$.

4.3 Establish MIMO channel array covariance matrix

After the correlation matrix was gained, MIMO channel array covariance matrix could be derived according to stated rule. Generally, the hypotheses below are rational.

Hypotheses one, the relativity of signals between antenna p transmitting antenna m receiving and antenna q transmitting antenna m receiving is independent of m.

Hypotheses two, the relativity of signals between antenna p transmitting antenna m receiving and antenna p transmitting antenna n receiving is independent of p.

Two hypotheses means the relativity among transmitting antenna is irrelevant to the relativity among receiving antenna. So the relativity of channel could be denoted as

$$E\left(h_{mp}h_{nq}^{*}\right)=E\left(h_{kp}h_{kq}^{*}\right)\cdot E\left(h_{ml}h_{nl}^{*}\right) \quad * \text{ denotes Conjugation} \tag{11}$$

Equation (11) shows, the relativity of two pair antenna could be figured as the product of corresponding relativity among transmitting antenna and relativity among receiving antenna. Equation (11) could be denoted by using matrix as below.

$$\boldsymbol{R}=\boldsymbol{R}_{Tx}\otimes\boldsymbol{R}_{Rx} \quad \otimes \text{ denotes Kronecker product} \tag{12}$$

In equation (12), $\boldsymbol{R}\overset{\Delta}{=}E\left[\mathrm{vec}(\boldsymbol{H})\mathrm{vec}(\boldsymbol{H})^{\mathrm{H}}\right]\in\boldsymbol{C}^{M_TM_R\times M_TM_{Rr}}$ （$\mathrm{vec}(\cdot)$ denotes line up according to row ） is defined as MIMO channel covariance matrix which has $M_TM_R\times M_TM_R$ dimensions, $\boldsymbol{R}_{Tx}\in\boldsymbol{C}^{M_T\times M_T}$ denotes covariance matrix of transmitting antenna, $\boldsymbol{R}_{Rx}\in\boldsymbol{C}^{M_R\times M_R}$ denotes covariance matrix of receiving antenna.

4.4 Establish MIMO frequency selectivity correlation channel

In the environment of rich scattering, if the space between the antenna is enough big, each branch of MIMO channel could be deemed to independent. If each branch is dependent, the correlation channel matrix $\boldsymbol{H}_R(l)$ could be achieved by multiplying correlation matrix of receiving end at the left and of transmitting end at the right as equation (13).

$$\boldsymbol{H}_R(l)=\boldsymbol{R}_{Rx}^{1/2}\boldsymbol{H}(l)\left(\boldsymbol{R}_{Tx}^{1/2}\right)^{\mathrm{T}} \tag{13}$$

$\boldsymbol{R}^{1/2}$ denotes square root matrix of $\boldsymbol{R}$, namely $\boldsymbol{R}=\boldsymbol{R}^{1/2}\left(\boldsymbol{R}^{1/2}\right)^{\mathrm{H}}$.

Equation (13) also could be expressed as

$$\mathrm{vec}(\boldsymbol{H}_R(l))=\boldsymbol{R}^{1/2}\mathrm{vec}(\boldsymbol{H}(l)) \tag{14}$$

From the point of statistic characteristic of $\boldsymbol{H}$, equation (13) and (14) is equivalent. So the channel gain which accords with given relativity could be achieved by using equation (14).

4.5 Establish time-varying frequency-selective MIMO channel

When channel is time-varying, channel model need to be established over again along with time-varying. This must result in great computation. So a new modeling scheme was provided. This scheme described in equation (15) takes account of the relativity at time and is applicable to time-varying communication environment.

$$\boldsymbol{H}_R^{n+1}(l)=\boldsymbol{R}_{Rx}^{1/2}\left[a\boldsymbol{H}^n(l)+\boldsymbol{V}(l)\right]\left(\boldsymbol{R}_{Tx}^{1/2}\right)^{\mathrm{T}} \tag{15}$$

In equation (15)

$$\boldsymbol{V}(l)=\begin{bmatrix} v_{11}(l) & v_{12}(l) & \cdots & v_{1M_R}(l) \\ v_{21}(l) & v_{22}(l) & \cdots & v_{2M_R}(l) \\ \vdots & \vdots & \ddots & \vdots \\ v_{M_T1}(l) & v_{M_T2}(l) & \cdots & v_{M_TM_R}(l) \end{bmatrix} \tag{16}$$

$v_{ij}(l)$ is Gauss noise whose mean is 0，variance is σ_v^2.

$$v_{ij}(l) = v_{ij}^c(l) + \mathrm{j}v_{ij}^s(l) \quad (17)$$

$1 \le i \le M_R$, $1 \le j \le M_T$, $0 \le l \le L-1$

$$v_{ij}^c(l) = \sigma_v \sqrt{\frac{2}{N_v}} \left[\sum_{k=1}^{M_v} 2\cos\frac{\pi k}{M_v} \cos\left(2\pi f_d l \cos\frac{2\pi k}{N_v} + \phi_i^v\right) + \cos\left(2\pi f_c l + \phi_0^v\right) \right] \quad (18)$$

$$v_{ij}^s(l) = \sigma_v \sqrt{\frac{2}{N_v}} \left[\sum_{k=1}^{M_v} 2\sin\frac{\pi k}{M_v} \sin\left(2\pi f_d l \cos\frac{2\pi k}{N_v} + \phi_i^v\right) + \cos\left(2\pi f_c l + \phi_0^v\right) \right] \quad (19)$$

In equation (18), (19), f_c is carrier wave frequency, f_d is maximum doppler frequency, N_v is the number of harmonic, $N_v = 4M_v + 2$, ϕ_i^v, $(i = 0,1,\cdots,M_v)$ obey submits to uniform distribution in $[0,2\pi)$. a is time correlation coefficient which reflects the speed of channel varying, $\boldsymbol{H}_R^n(l)$ could be achieved by equation (15). a and σ_v^2 could be achieved by equation (20),(21).

$$a = \mathrm{J}_0(2\pi f_d \Delta\tau) \quad (20)$$

$$\sigma_v^2 + a^2 = 1 \quad (21)$$

$\Delta\tau$ is time interval between the time of $n+1$ and the time of n. f_d is maximum doppler frequency. $\mathrm{J}_0(\cdot)$ denotes zero Bessel function.

By adopting this scheme of modeling could represent the relativity at space and time, besides decrease computation at repeating modeling.

5. Simulation of MIMO channel model

In the simulation, the MIMO system have two transmitting antenna and two receiving antenna which all are uniform array. At base terminal the power azimuth spectrum obeys Laplasse distribution. AS is 10°, AOD is 20°. At mobile terminal the power azimuth spectrum also obeys Laplasse distribution. AS is 30°, AOD is 67.5°. The Carrier frequency is 2.15GHz. The speed of mobile station is 120km/h, so the maximum Doppler frequency shift is 239Hz.

In the figures 1 and 2, Channel capacity of Ideal communication channel, not related channel, related channel and random channel under different signal to noise ratio have been simulated. In the figure 1, $d = 0.5\lambda$.in the figure 2, $d = 5\lambda$.These figures showed the arrangement of channel capacity from big to small is ideal communication channel, not related channel, related channel and random channel. The channel capacity of related channel is closer to not related channel in figure 2 than 1. The reason is the relevance of channels decrease when distance of antennas becomes larger. The related channel brought forward in this paper takes into account many factor in practical communication environment, so the channel capacity of this related channel could reflect practical MIMO channel capacity.

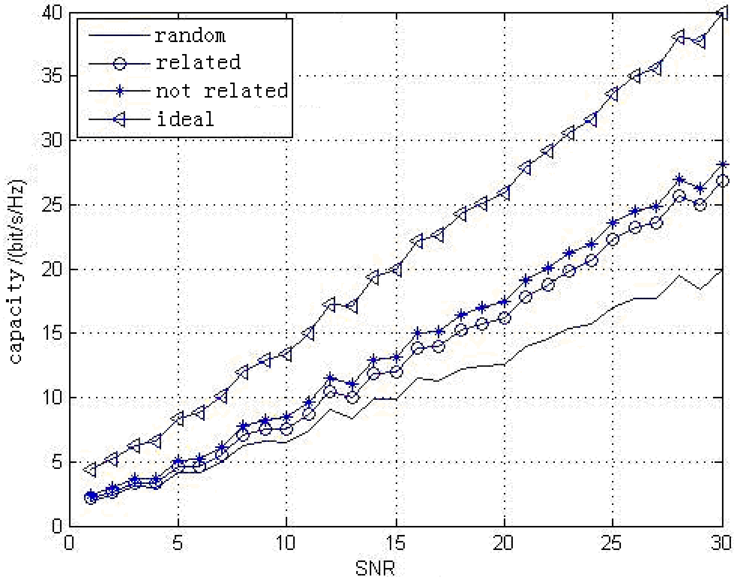

Figure1. MIMO channels capacity ($d = 0.5\lambda$)

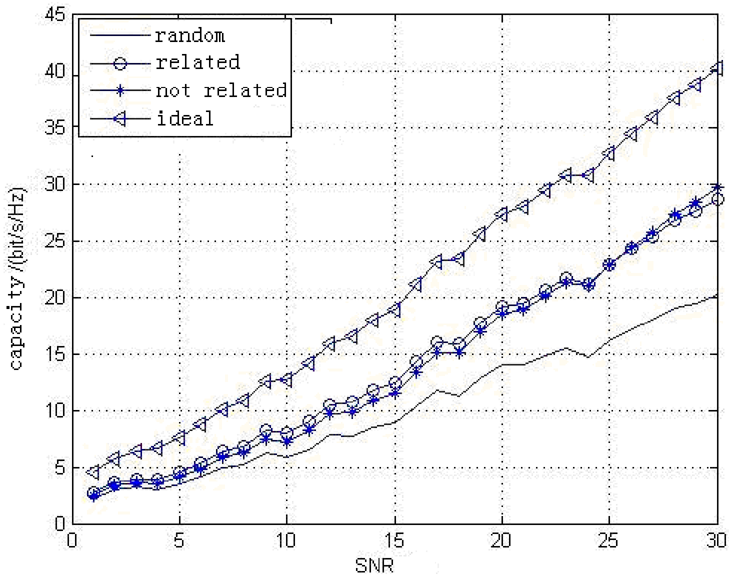

Figure 2. MIMO channels capacity ($d = 5\lambda$)

6. Conclusion

MIMO system has great potential in improving system capacity and quality. So MIMO system had been received continuous attention in recent years. The MIMO channel model is complex because MIMO channel involves many factors. In this paper, a kind of MIMO channel model is brought forward which has time selectivity, frequency selectivity, space selectivity. This model takes into account many factors in practical communication environment. Simulation shows this related channel capacity is consistent with theoretical channel capacity. Thereby the rationality of this modeling was validated. This model provides powerful implement for simulation of MIMO capability, analysis of system capacity and evaluation of performance.

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